Anchoring Technology for In Situ Exploration of Small Bodies[1]

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Abstract—Comets, asteroids and other small bodies found in the solar system do not possess enough gravity to ensure spacecraft contact forces sufficient to allow many types of in situ science, such as core or surface sampling. Some method of providing sufficient contact force must be used for successful in situ exploration. A range of possible anchoring technologies for use with small bodies is discussed and a specific technology developed in greater detail. This anchoring technology is based on a high energy, gas driven telescoping spike and has demonstrated success in anchoring to bodies with surface properties that may range in unconfined compressive strengths from 10^4 Pa to 10^7 Pa. The physics of the device and the penetration mechanics of the anchoring are discussed. The development of the hardware for NASA's now cancelled ST4/Champollion mission is detailed and finally, results from the test and verification program for the ST4/Champollion spacecraft anchoring mechanism are discussed.

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1. Introduction

In situ exploration of small bodies presents a great challenge that previous interplanetary missions have not faced. Comets, asteroids and other small bodies found in the solar system do not possess enough surface gravity to ensure sufficient spacecraft contact forces to allow many types of in situ science, such as drilling or surface sampling. For such bodies the term *landing* is not appropriate and the *docking* paradigm is better suited. In order to conduct in situ science, a spacecraft requires a method of anchoring itself to the small body.

ST4/Champollion was to be the fourth interplanetary spacecraft in NASA's New Millennium Program. Its mission was to travel on a two-and-a-half-year journey to the comet Tempel 1. After arriving at the comet, the spacecraft was to circle the comet's nucleus for several months, mapping it and analyzing the composition of the coma. After studying the comet from a distance, the spacecraft was then to become the first to land and anchor on the surface of a comet. This mission was very ambitious and would have been the first in situ mission to a small body. The effort was made all the more challenging by the fact that little is known about the physical properties of cometary materials.

There is thought to be a great range in the possible physical properties of cometary materials. Based on variations of possible chemical composition, thermal environment, thermal environmental history and mechanical processes acting on the material, cometary material properties are thought to fall within the wide range shown in Table 1.

Of greatest concern for anchoring are the mechanical properties. The possible range of unconfined compressive strengths, 10^2-10^8 Pa, represents a significant anchoring challenge. Anchoring into material with such a wide range of mechanical properties poses a novel problem. Further, the anchoring system must be designed to be successful without prior knowledge of the mechanical properties of the comet's surface.

It is expected that the cometary material is heterogeneous. It may well be that both low strength and high strength materials exist in the same region, each possessing length scales from 0.1-10 m. There may also be deep layers of nearly strengthless material on top of much stronger subsurface regions. This heterogeneity causes problems and suggests that a successful anchoring strategy should include provisions for anchoring into solid material at some depth below the apparent surface. The Comet Properties Science Group (CPSG), assembled by the Champollion project to define potential comet material properties and configurations has determined a large range of possible material properties, as shown in Table 1, and wide range of possible distributions of these various material properties. The potential for nearly strengthless material near the surface and more solid material as much as 1-2 m below the surface is a possible subsurface configuration and drives anchoring considerations. This suggests an anchor design that can anchor to at least 3 m.

Table 1. CPSG Comet Physical Properties Estimates

Parameter	Weak Region	Typical	Strong Region
Porosity	80%	30%	10%
Mantle Density (g/cm3)	.02	.5	1
Thermal Conductivity (W/m-K)	.05	1	3
Specific Heat (J/kg-K)	70	120	2000
Compression Strength (Pa)	10^2	10^5	10^8
Dynamic Tensile Strength (Pa)	10	10^4	10^7

In service of the now cancelled ST4/Champollion mission, JPL developed a technology for anchoring spacecraft (S/C) to a comet's surface. This anchoring technology is based on a high energy, gas driven telescoping spike and has demonstrated success in anchoring to simulants with surface properties that range in unconfined compressive strengths from 10^4 Pa to 10^7 Pa. This range of strengths corresponds to a large subset of possible cometary material strengths.

Further, the ST4/Champollion anchor has demonstrated anchoring success in material that have mechanical properties similar to those of terrestrial rocky material. This suggests possible extension of this technology for use with in situ exploration of small rocky bodies.

The goal of this paper is to inform the in situ exploration community about the development and performance of the ST4/Champollion anchor. The organization of the paper is as follows. We begin with a discussion of possible anchoring solutions that have been considered during the development of the ST4/Champollion anchor. This discussion is qualitative, as complete technical treatment of all the possible trade studies is beyond the scope of this paper. We then define and discuss the ST4/Champollion anchor technology, including the relative physics, and give a brief treatment of the penetration mechanics model used in the development of the anchoring system. Next, we describe the testing program that has been used as an integral part of the development process, including a treatment of the test results and model validation. Finally we conclude and give suggestions for future applications of this anchoring technology.

2. Anchor Requirements

The requirements of the anchoring system were to have the capability to anchor to a very irregular surface with uncertain material properties, and to provide at least 450N pull-out resistance in any direction. Additionally, the anchor was to have minimal mechanical and thermal impact on the comet material, and generate minimal impact on the design of the spacecraft. Because of the uncertainty in comet material properties and topography, the ST4/Champollion mission desired an anchor depth of up to 3m.

3. Anchoring Technologies

There are perhaps an infinite number of possible designs to anchor a spacecraft to a comet surface. In service of the ST4/Champollion mission, several candidates were investigated. Below, some possible anchoring methods are discussed.

Slow Anchoring Methods

Slow anchoring involves using minimal forces and developing a mechanical link between the spacecraft and the comet surface over time. Because reaction forces are being applied to the spacecraft by this anchoring process, some type of thrusters must be used to hold the spacecraft against the comet surface. In general this requires that attitude control be involved and significant additional fuel be consumed during the anchoring process.

Drill —This strategy employs one or two drills to bore a hole into the comet in order to anchor the S/C. Two counter rotating drills relieve the need to stabilize the S/C against rotation about the drill axis. The drill concept is shown in Figure 1.

Pros:

1. Minimal thermal impact to the surface region can be achieved by slow drilling.

Cons:

1. Drilling is a slow operation. The drilling time required is large and the force that must be exerted on the drill is in the range of 50N. This drives requirements on thruster fuel. Calculations of fuel mass required suggest this option is unattractive. Additionally, the long station keeping time increases demands on the attitude control system (ACS) and increases ACS risk.

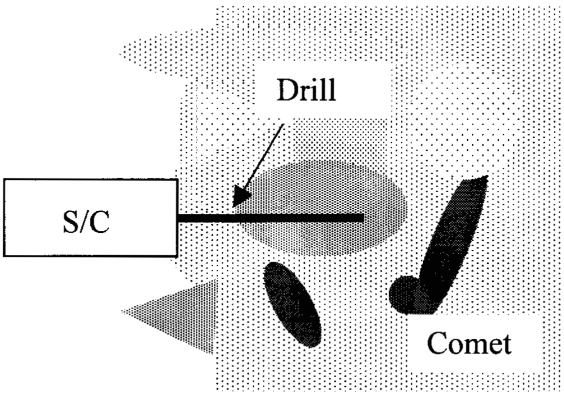

Figure 1. Drill Concept

Melter—This strategy employs a heated probe to melt a hole into the comet. An expansion device would then be used to fix the probe into the hole. The melter concept is shown in Figure 2.

Pros:

1. A melter system can be designed with few moving parts which reduces cost, mass and mechanism related uncertainty.

Cons:

1. Melting is an energy intensive procedure. Spacecraft power would typically be too limited to use an electric heater since the melting times are long and therefore thruster fuel mass used to keep the S/C positioned is large. Additionally, the long station keeping time increases demands on the ACS and increases ACS risk.
2. Given the heterogeneous and uncertain composition of the comet's surface, melting is a high risk procedure. It may be possible to encounter materials that do not liquify or sublime at sufficient rate given the temperatures generated by a melter.

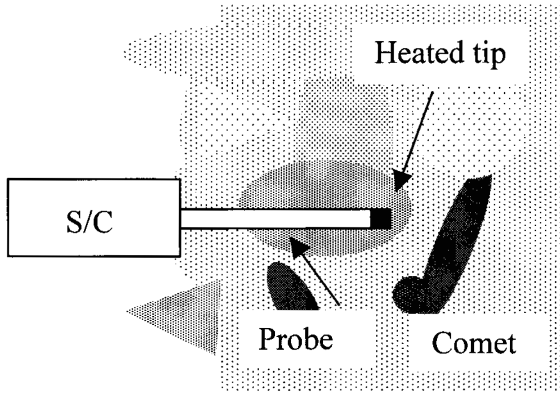

Figure 2. Melter Concept

High-Speed Anchoring

All high-speed methods of anchoring have the advantage that they do not require the spacecraft to be held against the comet for an appreciable amount of time. These methods rely on explosively driven devices that can be designed in such a way that there is no net momentum transferred directly to the spacecraft. It is of note that high energies are involved to allow the penetration of potentially high strength comet materials. If the comet proves to be low strength, this energy is not transferred to the comet material and must be dissipated within the anchoring system. The following concepts assume such momentum compensation.

Tethered Spike—This method employs an explosively driven spike that enters the comet surface and comes to rest lodged at some depth. Behind the projectile, a tether is dragged and once the penetration is complete the tether is retracted until taught.

As the tether is being dragged out, during the penetration process, a friction force can be applied to the tether spool. This force can dissipate energy if the comet material proves very low in strength. The maximum depth of the penetration is governed by the tether length, the friction force and the initial kinetic energy of the spike. The tethered spike concept is shown in Figure 3.

Pros:

1. It is possible to tailor the friction force acting on the tether and thereby tailor the design's kinetic energy vs. depth relationship based on estimates of the comet subsurface material property distribution.
2. Little additional fuel mass is required to stabilize the S/C during anchoring.

Cons:

1. In a heterogeneous target such as the anticipated comet material, deflection of the spike from its intended path is very likely to occur. Knowledge of the location of the spike once it has come to rest is not guaranteed. It is concluded that tensioning of the

tether may result in an unacceptable orientation of the spacecraft.
2. During retraction of the tether, it may be difficult to sense whether the tension in the tether is due to taking up slack from the potentially twisted path which the spike has traveled or whether this tension force is the un-seating of a weakly anchored spike.
3. This design cannot stabilize the S/C during "landing" because the tether is slack. For this reason the ACS must be engaged until the tether is taught.
4. The tether can only provide a tension force in a single direction. Moment and shear bearing capacity must come from interaction between the S/C and the material directly below it as shown in Figure 3. If this material has very low strength, the fixity of the S/C to the comet is jeopardized.

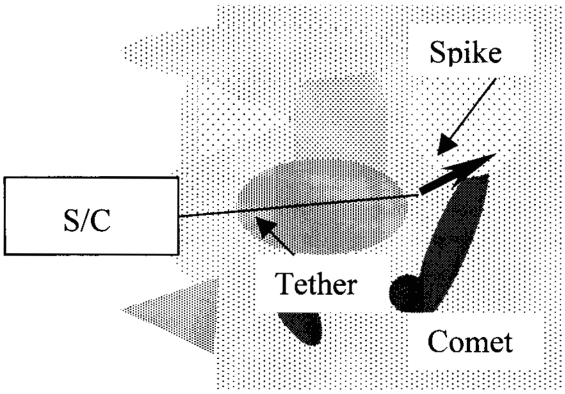

Figure 3. Tether Spike Concept

Telescoping Spike—An explosively driven spike is nested within several concentric tubes of increasing diameters. Each tube has a necked down region on the comet facing end and an enlarged diameter at the other end. These tubes fit tightly with one and other in such a way to provide interface forces to supply the required anchoring loads.

As the spike emerges from the S/C it draws out the first tube and then the remaining tubes in sequence, forming a rigid shaft. If penetration forces bring the assembly to rest prior to full deployment, a mechanical connection between the comet and the S/C still exists through the nested tube contact forces. The telescoping spike concept is shown in Figure 4.

Pros:
1. This design allows for near immediate stabilization of the "landing" event.
2. The telescoping spike provides axial, moment and shear carrying capacity and therefore is more stable and can operate over a wider set of material properties than the tethered spike.
3. No additional fuel mass is required to stabilize the S/C during anchoring.

Cons:
1. Large lateral loads may be imparted to the S/C in the anchoring process due to oblique features in the heterogeneous cometary material.
2. It is more difficult to tailor the design's kinetic energy vs. depth relationship because this requires changes in the mass of the telescoping tubes. These mass properties are influenced by other design considerations such as strength and thermal concerns.

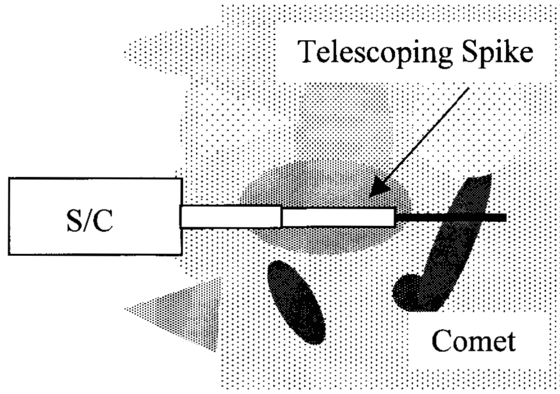

Figure 4. Telescoping Spike Concept

Multi-legged with Tethered or Telescoping Spikes— Both of the above methods can be used to anchor feet or landing pads on a multi-legged lander. In such a system the tethered or telescoping spikes act as above.

The multi-legged lander is particularly useful for the tethered spike concept. The three legs allow for moment restraint capability that is not present, in general, with a single tethered spike configuration. The three legged tethered spike concept is shown in Figure 5.

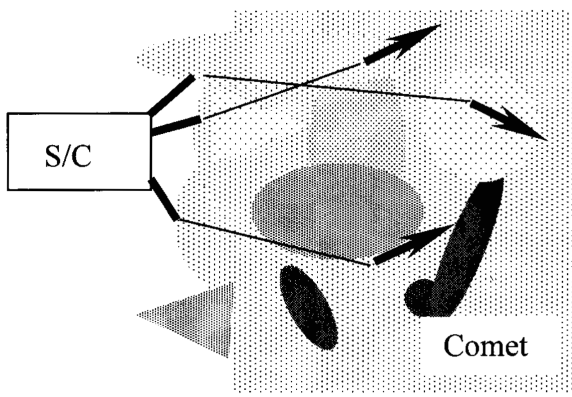

Figure 5. Three Legged Tether Spike Concept

Unfortunately, multiple legs increase the interaction with an unknown and potentially very rough surface. Landing sites become more restrictive and risk is increased. Additionally, each penetrating spike, be it tethered or telescoping, must have enough initial kinetic energy to penetrate potentially hard cometary materials to sufficient depth. This comes at the cost of mass. Three such penetrators may prove very massive.

4. THE ST4/CHAMPOLLION ANCHOR

The telescoping spike technology was chosen for the ST4/Champollion anchor. The anchor consists of a spike plus two telescoping tubes, allowing the spike to extend up to approximately 3 meters. The spike is nested concentrically within the two telescoping tubes. As the spacecraft approaches the comet, the anchor system is triggered by a laser altimeter that senses the proximity of the surface. The spike, initially attached to a piston, is accelerated to a desired velocity by a gas generator that consists of a cartridge initiated by dual redundant electro-explosive devices. At the end of the piston stroke, the spike will break free and continue traveling, extending the two tubes in a telescoping fashion, while the piston will be trapped by the chamber, forming a seal to preclude leakage and minimize any contamination of the comet surface.

The gas generator attachment allows the entire gas generator to breakaway upon ignition and thus the gas generator acts as a reaction mass in order to minimize the shock felt by the spacecraft and yield a momentum compensated device.

Anchor Dynamics

The ST4/Champollion anchoring system involved the transfer of momentum and energy between various components of the system. Below we discuss the important points.

Ignoring details of the gas generator system, we can consider the anchoring system as a five mass system. A schematic of the anchoring system is shown in Figure 6. Energy and momentum shuttle between the masses shown in figure 6 and this process is discussed below.

During deployment the gas generator acts as a reaction mass, breaking free of the S/C via low strength shear pins. Gas pressure between the spike and the gas generator drive the two masses apart. This imparts kinetic energy to the spike with no net momentum to the S/C since the gas generator mass essentially decouples from the S/C. If the spike immediately encounters hard comet material after leaving the S/C it dissipates the kinetic energy in the penetration process and transfers its momentum to the comet. If little energy is dissipated during early penetration, the spike continues to enter the comet material. Eventually, the spike begins to couple with the first tube. The coupling is accomplished by plastic deformation of the tube as its smaller diameter is enlarged. This process dissipates energy. After coupling, the spike/tube #1 system is moving at a slower velocity than the spike alone. If the penetration forces are still low, the spike continues to enter the comet material and eventually tube #2 and the S/C are coupled into this system.

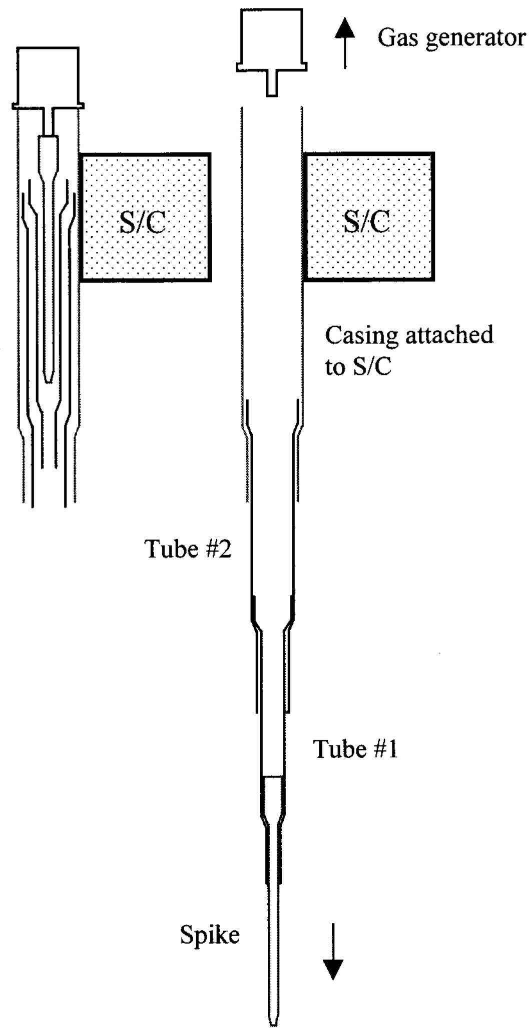

Figure 6. Schematic of Telescoping Spike System

Momentum and energy balance indicate that for a 100 kg S/C and a 2.3 kg spike initially travelling at 120 m/s, as much as 98% of the initial kinetic energy of the spike must be absorbed into the telescoping hardware. The challenge is to design the hardware to absorb this energy and yet retain as much energy as possible as the deployment progresses, in order to penetrate potentially hard sub-surface cometary materials. Not only must the anchoring system be designed to absorb essentially all of the initial kinetic energy, but it must be designed to absorb it in a specific manner.

Consider the first coupling event between the spike and the first tube. Let m_s, m_{t1}, m_{t2}, and $m_{s/c}$ be the mass of the spike, first tube, second tube and S/C respectively. Also let E_0, E_1 and ΔE_1 be the initial kinetic energy, post coupling kinetic energy and the kinetic energy loss. If the initial spike velocity is v_s we have

$$
E_0 = \frac{1}{2} m_s v_s^2
$$

$$
\Delta E_1 = \frac{1}{2} m_s v_s^2 \left[1 - \frac{m_s}{m_s + m_{t1}} \right] \qquad (1)
$$

$$
E_1 = \frac{1}{2} m_s v_s^2 \left[\frac{m_s}{m_s + m_{t1}} \right]
$$

This relationship can be generalized for any number of stages present in a telescoping spike anchoring system. Considering a system with n elements with mass m_1, m_2, ..., m_n, we then can form an expression for the energy after the i[th] coupling has occurred.

$$
E_i = E_0 \prod_{k=1}^{i} M_k,
$$

$$
M_k = \frac{m_1 + m_2 + \cdots + m_k}{m_1 + m_2 + \cdots + m_{k+1}} \qquad (2)
$$

Here we have defined M_k as the ratio of the pre-coupled mass divided by the post coupled mass. It can be seen from Eq. (2) that energy distribution with depth is obtained by varying the masses of the various stages. In general it is desired to retain energy to as great a depth as possible, to allow for the possibility of a deep layer of nearly strengthless material on top of high strength material. This drives the tubes to be as low in mass as practical. The distribution of maximum energy with depth for the ST4/Champollion anchor is shown below in Figure 7.

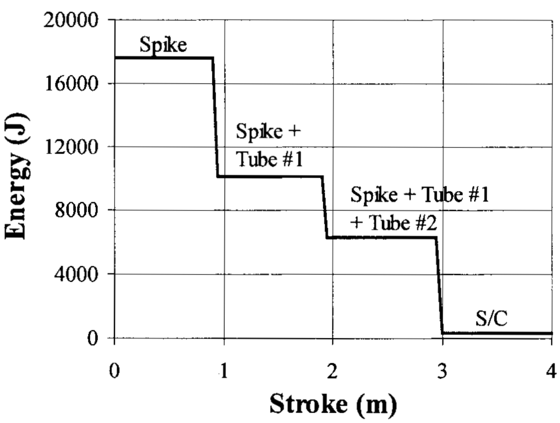

Figure 7. Maximum Kinetic Energy with Anchor Depth.

Stage Coupling

As mentioned above, various stages are coupled together using plastic deformation of the stage itself. Here we describe in more detail this design feature.

The coupling of stages of the telescoping spike anchor requires dissipation of energy. In general, the maximum energy that must be dissipated during the i[th] coupling is given by

$$
\Delta E_i = E_0 \left[\prod_{k=1}^{i-1} M_k \right] (1 - M_i) \qquad (3)
$$

Several possible energy dissipation methods were investigated including the use of crushable aluminum honeycomb material. It was determined that the most mass efficient and reliable method was swaging the tubes together. To illustrate this consider the spike and first tube coupling. The first tube has both small and large diameter sections as shown in Figure 8.

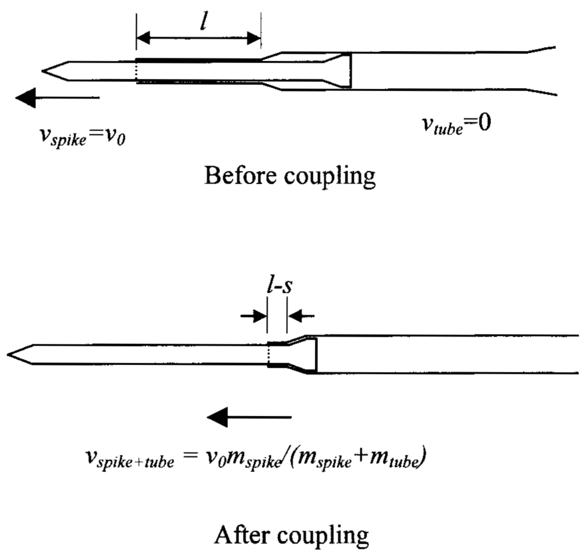

Figure 8. Stage Coupling through Swaging

A length s of the smaller diameter section is plastically deformed to the larger diameter during coupling. This process, known as swaging, dissipates the required energy while using only the material needed for the anchor itself. Additionally this coupling has proven strong enough to withstand the rigors of penetration into materials of compressive strengths of 10^6-10^7 Pa. Results from tests described below indicate that this design functions reliably and can support all the required forces and moments for anchor integrity.

Penetration Mechanics

Here we outline the penetration mechanics model used to analyze the anchor design and help guide the technology development.

Penetration of earthen materials, frozen earth and ices by cylindrical bodies has been studied in some detail [1-6]. The spherical cavity expansion model of Bishop, Hill and

Mott [7] has been developed to provide accurate modeling of the penetration process in soils [6]. M. J. Forrestal, et. al. [8] has extended the form of this solution for use as an empirical relationship to describe the penetration of concrete targets. This form was adopted for use in the Champollion penetration mechanics analysis. Equation (4) shows a simplified form of the resulting penetration force equation.

$$F = \pi a^2 \left[D + \rho N V^2\right] \tag{4}$$

Here, F is the penetration resistance, a is the penetrator radius, D is an empirical target strength related parameter, ρ is the density of the target material, N is coefficient associated with the nose geometry and V is the instantaneous velocity of the penetrator. It can be shown by non-dimensionalization of Eq. (4) that this model for penetration resistance force can generate penetration depth verse impact velocity relationships. These relationships are either momentum or energy driven and have been described empirically in [1], [5].

5 THE ST4/CHAMPOLLION ANCHORING TESTS

The ST4/Champollion anchoring tests were conducted at the China lake Naval Air Warfare Center in China Lake, California. The test set-up utilized a 15 cm bore compressed air gun firing horizontally into cylindrical comet simulant targets whose long axis were aligned with the barrel of the gun. The air gun barrel was formed from two 15 cm diameter steel tubes bolted together to form a 12 m long stroke gun. The gun was powered by a 1,135 liter tank with a maximum pressure approximately of 800 kPa. A separate high pressure line was used to actuate an arm that opened the valve to the main tank, firing the gun.

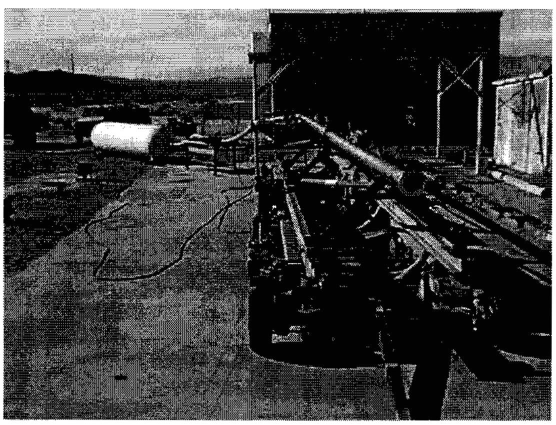

Figure 9. Airgun Used in Anchor Testing

High speed video was used to obtain almost instantaneous velocity measurements as well as to verify that the penetrator exited the barrel straight and hit the target with zero angle of attack. Two camera heads, one perpendicular to the flight path to measure velocity and one at an oblique angle to watch the impact plane, recorded images of the penetrator leaving the barrel and striking the target.

The purpose of the first series of anchoring tests was to select a nose shape for the tip of the anchoring penetrator, referred to as the spike. In particular, the nose characteristics that were focused on included ricochet resistance, penetration characteristics, and survivability. The test variables were simulant type, impact angle (defined as the angle between the target surface normal and the penetrator long axis), velocity, nose type, and nose aspect ratio. The mass and diameter of the penetrators remained constant, at 1.0 kg and 1.9 cm respectively.

The planned penetrator velocities were 100 m/s and 170 m/s. The lower velocity was to be used during the ricochet tests, since literature suggested that the worst case ricochet condition is at lower velocities. The higher velocity was to be used during the normal impacts, from which penetration depth would be measured and checked for any nose damage.

The primary simulant used as targets in the testing was a cement based mixture with small aggregate and a compressive strength of approximately 2.86e7 Pa, designed by JPL scientist Dr. Jacklyn Green. In addition, it was thought to be useful to employ a "harder" comet simulant material. The second material, also designed by Dr. Green, was cement with a super plasticiser, silica fume, fly ash, and an accelerator that had a compressive strength of approximately 5.21e7 Pa.

The normal targets were simulant filled cardboard tubes measuring 76.2 cm diameter by ~91 cm long, with a 21 day cure time. These normal targets weighed approximately 900 kg. For the ricochet test targets, an angled piece of foam was inserted into the tubes before the targets were poured, resulting in a 45 degree angled face. The targets were placed in a cradle made of steel, and large concrete blocks were placed against the backside of the target, preventing it from sliding backwards upon penetration.

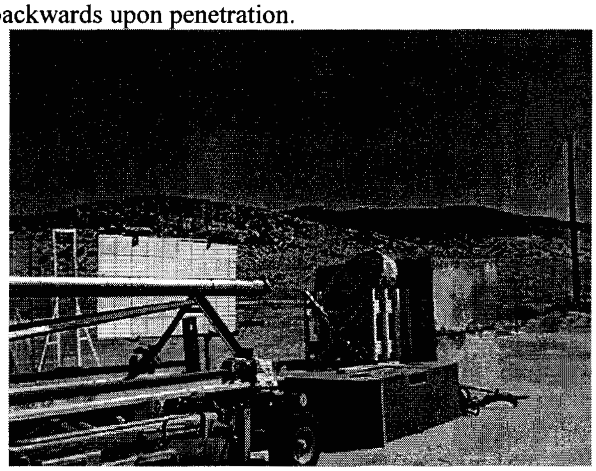

Figure 10. Angled Target Placed against Concrete Block

The two nose types that were tested were ogive (an arc of a circle which is tangent to the penetrator shank) and conic. The ogive was selected because it is commonly found in the literature [1, 6, 8]. The conic was selected because it is another popular nose type with a good literature base. It is generally agreed that there is an inverse relationship between ricochet resistance and penetration depth; i.e. as the nose gets stubbier, ricochet resistance improves but penetration depth decreases.

Penetrators with nose aspect ratios of 2:1 and 3:1 were machined for the test series. The 3:1 was expected to have better penetration than the 2:1, but poorer ricochet resistance.

A 1.9 cm diameter was selected for the spike since that had been used in the previous prototype tests, and therefore surplus material could be utilized at a significant cost savings.

A mass of 1 kg was chosen as a worst case ricochet case, since it was the lower bound of the anticipated spike mass range (according to literature, a lower mass penetrator is more likely to ricochet than one of higher mass).

During testing, it was observed that the nose shapes failed to penetrate the targets at 45 degrees incidence angles and so the nose shapes under consideration were reevaluated. 3:1 ogive noses recovered from ricocheted penetrators showed little damage and were thought to be worth further investigation. The poor performance of all the pointed nose shapes, both conic and ogive, lead to the consideration of blunted designs. Truncated conic nose shapes were therefore investigated.

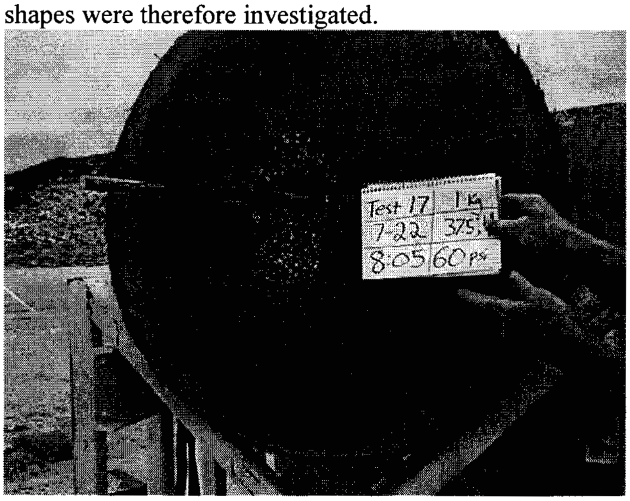

Fig 11. Penetrator into a 2.86e7 Pa target at a 37.5 Impact Angle

Tests were undertaken to find the actual critical ricochet angle for the 3:1 ogive and two types of 3:1 truncated cones. The truncated cones were truncated with 1/2 (3:1-1/2) and 2/3 (3:1-2/3) of their original lengths removed. Early comparative tests suggested that the 3:1-1/2 truncated cone performed better. The 3:1-2/3 provided only a finger loose pull-out force and the 3:1-1/2 provided ~7,000 N of pull-out force, both at 37.5 degrees of impact inclination into the 2.86e7 Pa simulant.

Figure 12. 3:1-1/2 Truncated Cone Nose

After the ricochet and anchoring capabilities had been investigated, the remaining targets were used to compare the standard normal penetration response of the two different nose types into targets of the softer, 2.86e7 Pa simulant. The noses gave similar normal penetration results.

These results lead to the selection of the 3:1-1/2 truncated cone as the nose baseline. Only this design was investigated further.

The second major group of anchoring tests was conducted in an effort to further characterize the selected 3:1-1/2 truncated cone nose shape.

Tests were performed with 1.0 kg, 3:1-1/2 truncated cone nose, 1.9 cm diameter penetrators. These penetrators were fired into 6, 8, 30, and 60 MPa unconfined compressive strength concrete targets at impact angles of up to 70 degrees. The ricochet characteristics are plotted in Figures 13-16, with interpretive lines drawn to separate the ricochet and penetration regions. The area between the lines represents an area of uncertainty, where the penetrators did not ricochet but were "finger-loose" or where there is probability of either ricochet or penetration. There is a large measure of uncertainty in the shape and boundaries of the various regions.

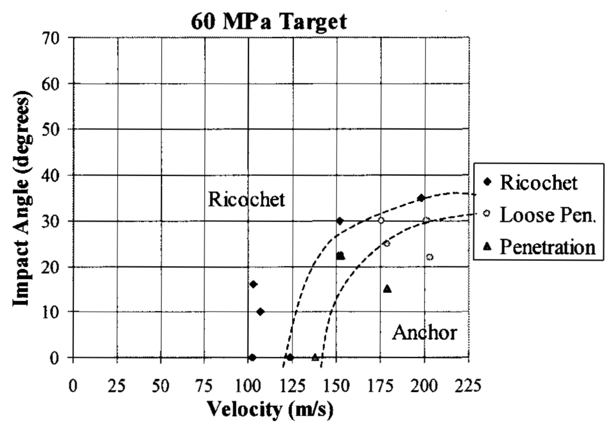

Figure 13. Anchoring Threshold Results for Targets with 60 MPa Compressive Strength

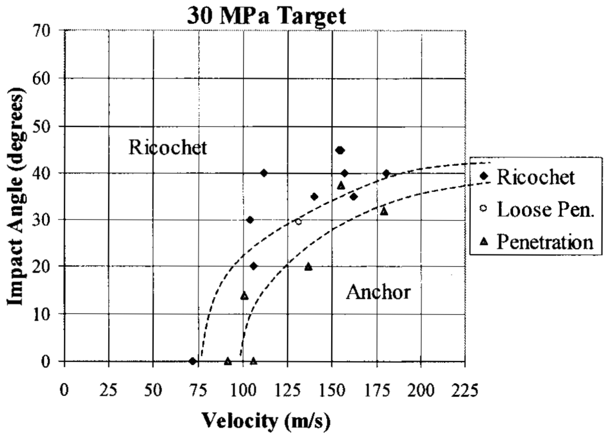

Figure 14. Anchoring Threshold Results for Targets with 30 MPa Compressive Strength

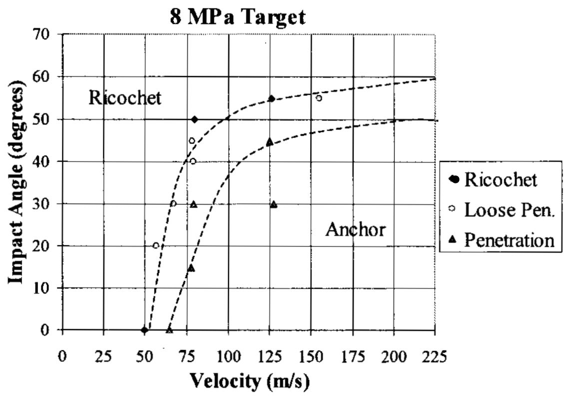

Figure 15. Anchoring Threshold Results for Targets with 8 MPa Compressive Strength

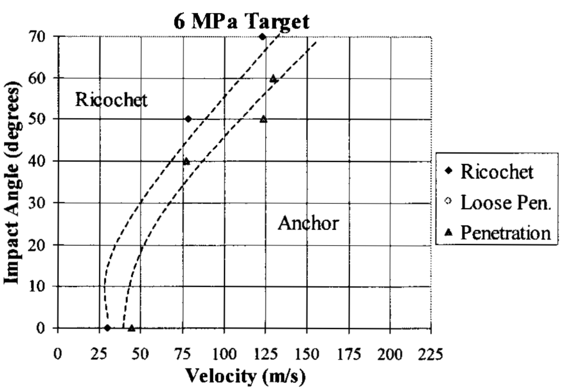

Figure 16. Anchoring Threshold Results for Targets with 6 MPa Compressive Strength

The ST4/Champollion mission had a requirement of anchoring securely, with a minimum of 444 N pull-out resistance in any direction, at impact angles of up to 45 degrees. Based on the above ricochet results, it was concluded that the 1 kg, 1.9 cm diameter penetrator could successfully anchor into materials of up to ~10 MPa with a 45 degree impact angle within a reasonable velocity range. It should be noted that even relatively high velocities could not guarantee a successful anchoring at a 45 degree impact angle into the 30 and 60 MPa targets.

Along with ricochet characterization, an additional goal of this test series was to develop a model to predict penetration depth given a penetrator mass and impact velocity. To achieve this objective, three groups of three 1.3 kg penetrators were fired into 30 MPa, 0 degree impact angle targets at various velocities. The averages of these groups of three are plotted on the graph below, along with
the best fit energy and momentum lines, and the penetration model based on Forrestal's work [8].

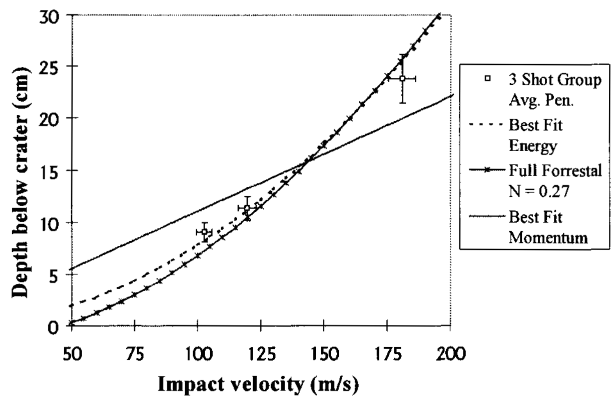

Figure 17. Penetration Depth vs. Impact Velocity

It should be noted that the penetration depth averages follow the best fit energy line much more closely than the best fit momentum line. This implies that penetration depth is more accurately predicted by kinetic energy than momentum.

The third major set of anchoring tests was conducted to investigate how the spike would "grab" the first telescoping leg. As the spike picks up and accelerates the first leg, momentum is conserved but kinetic energy is not. That energy needs to be dissipated by plastic deformation, or else the spike would rip through the first tube and leave it behind. Two different methods were investigated: a honeycomb crushable tube and a swaging process.

The first method called for a honeycomb crushable tube to be placed inside of the leg. A step machined into the spike would strike the end of the crushable, and compress it while the leg was accelerated.

The second method involves the spike "swaging" the first leg. The leg has a necked-down, smaller diameter "collar" region at the front of the leg. The corresponding spike has a gentle slope ramping up to a larger diameter section at the rear of the spike. As the spike slides through the leg, the larger diameter portion of the spike swages, or increases the diameter through plastic deformation, of the collar region of the leg and locks the two pieces together.

In order to have the ability to examine an unblemished spike/leg combination, a method of gently slowing down the projectile was required. The most practical, convenient way of providing this was by using a long barrel filled with water placed in line with the airgun. A plexiglass plate bolted to the end of the barrel contained the water until the spike/leg combination punctured it and continued into the water. By adjusting the size of a plastic cone attached to the leg, the drag force experienced by the penetrator was modified, thus tailoring the stopping distance.

For these tests, the leg was loosely held at the end of the air gun barrel, and was picked up by the spike after the spike had already been fully accelerated. The spike/leg combination then continued on towards the target or water barrel.

Both the crushable tube and swaging methods proved successful in water and simulant tests. The swaging method was chosen to be the baseline design since the necessary diameter change in the leg is much less than with the honeycomb method, which improves penetration into harder materials.

The fourth set of anchoring tests investigated the characteristics of the spike/tube combination into both heterogeneous and homogenous simulants, using the swaging method of energy dissipation. Penetrators were fired into 10MPa unconfined compressive strength homogeneous targets, as well as layered, heterogeneous targets that had a ~5 cm hard crust over a soft foam, with a 10 MPa base. The hard bases were formed at 0, 25, and 40 degree angles so that impact angles could be investigated.

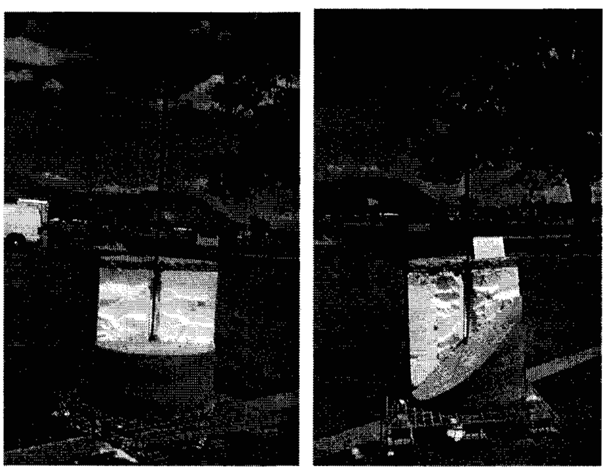

Figure 18. Spike and First Leg Fired into Heterogeneous, 0 and 40 Degree Targets (top section of material cut away)

In this set of tests, the spikes had a mass of 2.3 kg, diameter of 1.84 cm, and were 1 m long. The first legs were 1.8 kg and 1.54 m long.

When the spikes were fired at approximately 120 m/s, the spike and leg penetrated a homogeneous, 10 MPa target approximately 30 cm with a 0 degree impact angle. When the impact angle was increased to 45 degrees, the spike and tube penetrated approximately 25 cm and anchored securely.

In tests with the heterogeneous targets, the spikes were fired at 120 m/s and the spike and leg penetrated the crust/foam and securely anchored into the 10 MPa base. There was no significant difference in the depth of penetration for the 0, 25, and 40 degree base angles; in each case the spike was imbedded approximately 13 cm.

6. CONCLUSION

We have discussed the design and development of a new technology for anchoring spacecraft to small bodies. This anchoring method was developed for use in attaching the 500 kg, ST4/Champollion spacecraft to the surface of a comet. It is possible to use this anchoring design to attach to other small bodies such as asteroids or small moons. This technology allows in situ scientific exploration in the presence of small surface gravity.

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